Benchmark Planes for Higgs-to-Higgs Decays in the NMSSM

Ulrich Ellwanger, IJClab Orsay

With Cyril Hugonie, Université de Montpellier

Searches for new particles beyond the SM at the LHC are difficult if

- light new particles have small production cross sections, and
- heavy new particles with larger production cross sections undergo dominantly cascade decays.

Such scenarios are realized in the Higgs sector in large regions of the parameter space of the NMSSM

The Higgs Sector of the CP-conserving NMSSM:

- 3 CP-even scalars: h, H, H_S where h $\simeq$ SM-like, H $\simeq$ MSSM-like, $H_S \simeq$ singlet-like
- 2 CP-odd scalars: A, A_S where A $\simeq$ MSSM-like, $A_S \simeq$ singlet-like
- 1 complex charged $H^\pm$

H, A and $H^\pm$ form a nearly degenerate SU(2) doublet with masses $\gtrsim 400$ GeV due to constraints on $M_{H^\pm}$ from $b \to s + \gamma$ and direct searches.

H_S and A_S can have (independent) masses from very light to very heavy. They have small production cross sections, but can be produced in cascade decays of H, A.

$\to$ The only – but a promising – way to discover them

Relevant Higgs-to-Higgs Decays:

- $H \to h + H_S$: Recent searches:
  - CMS for $h \to \tau\tau, H_S \to b\bar{b}$ in JHEP 11 (2021), 057
  - CMS for $h \to b\bar{b}, H_S \to b\bar{b}$ in CMS-PAS-B2G-21-003

  If $H_S \to h + h$: Triple Higgs production!

- $A \to h + A_S$: Same final states, but:
  A_S can decouple from all gauge bosons and Fermions
  $\to$ the loop induced decays $A_S \to \gamma\gamma$, $A_S \to Z\gamma$ can be dominant!
  $\to$ large Xsections for $ggF \to A \to h + (A_S \to \gamma\gamma)$ are possible!
  (No published search yet)

- $H/H_S \to h + h$: Resonant Higgs pair production, recent searches:
  - ATLAS in ATLAS-CONF-2021-052, combination of $b\bar{b} + (b\bar{b}, \tau\tau, \gamma\gamma)$
  - CMS in arXiv:2112.03161: Lorentz-boosted Higgses in $b\bar{b}$+leptons

Relevant Higgs-to-Higgs Decays incl. Z:

- $A \to Z + h$: Recent searches:
  - CMS with $h \to b\bar{b}$ in Eur. Phys. J. C 79 (2019) no.7 (36 fb^{-1}),
  - CMS with $h \to \tau\tau$ in JHEP 03 (2020), 065 (36 fb^{-1}),
  - ATLAS with $h \to b\bar{b}$ in ATLAS-CONF-2020-043 (139 fb^{-1})
- $A \to Z + H_S$:
  - CMS with $H_S \to b\bar{b}$ in JHEP 03 (2020) 055
    (re-interpretation of $H \to Z + (A \to b\bar{b})$)
  - ATLAS with $H_S \to b\bar{b}/WW$ in Eur. Phys. J. C 81 (2021) no.5, 396

How large can these Xsections be in the NMSSM?

Which searches constrain the parameter space of the NMSSM?

Strategy: Use a dedicated Monte Carlo routine based on NMSSMTools, maximize Xsections for specified BSM Higgs masses,
satisfying existing constraints:

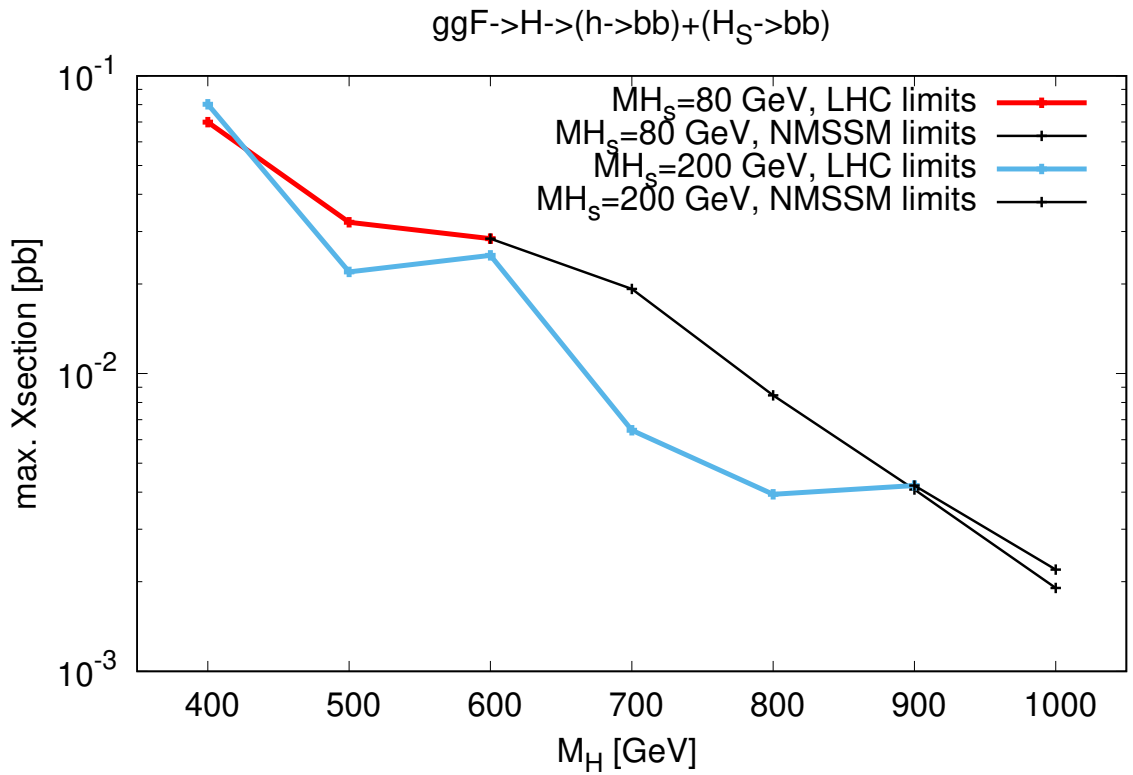
- Properties of h: $M_h = 125 \pm 2$ GeV and couplings in the κ framework
- Constraints from LEP, LHC (many!!!), B-physics
- Dark Matter: The LSP in the NMSSM is stable, contributes to the DM relic density
  $\rightarrow$ it must satisfy constraints from direct detection experiments!
  here: allow for additional contributions to DM from physics (far) above the weak scale (otherwise: not all combinations of BSM Higgs masses are possible).
  $\rightarrow$ Still: need fast enough LSP annihilation, typically via A_S in the s-channel
  $\rightarrow$ direct detection experiments impose constraints on the same parameters which determine the BSM Higgs masses and couplings!

→ Benchmark planes/lines (arXiv:2203.05049) for

- $ggF \to H \to (H_S \to bb) + (h \to XX)$, $XX = bb, \tau\tau, \gamma\gamma$
- $ggF \to H \to (H_S \to h + h) + h$ (Not searched yet)
- $ggF \to H \to (H_S \to tt) + h$ (Not searched yet)
- $ggF \to A \to (h \to \tau\tau) + (A_S \to \gamma\gamma)$
- $ggF \to H_2 \to h + h$ (H_2= mixture of H and H_S)
- $ggF \to A \to Z + (H_S \to XX)$, $XX = bb, \tau\tau, \gamma\gamma$
- $ggF \to A \to Z + (H_S \to h + h)$ (Not searched yet)
- $ggF \to A \to Z + (H_S \to tt)$ (Not searched yet)
- $ggF \to A \to Z + h$

H/A production cross sections for 13 TeV (ggF):
From BSM Higgs production cross sections in CERN Report4 2016, multiplied by the reduced couplings squared of H/A.
(This captures most of the radiative QCD corrections in the form of K-factors; remaining theoretical uncertainties at most of $\mathcal{O}(10\%)$).

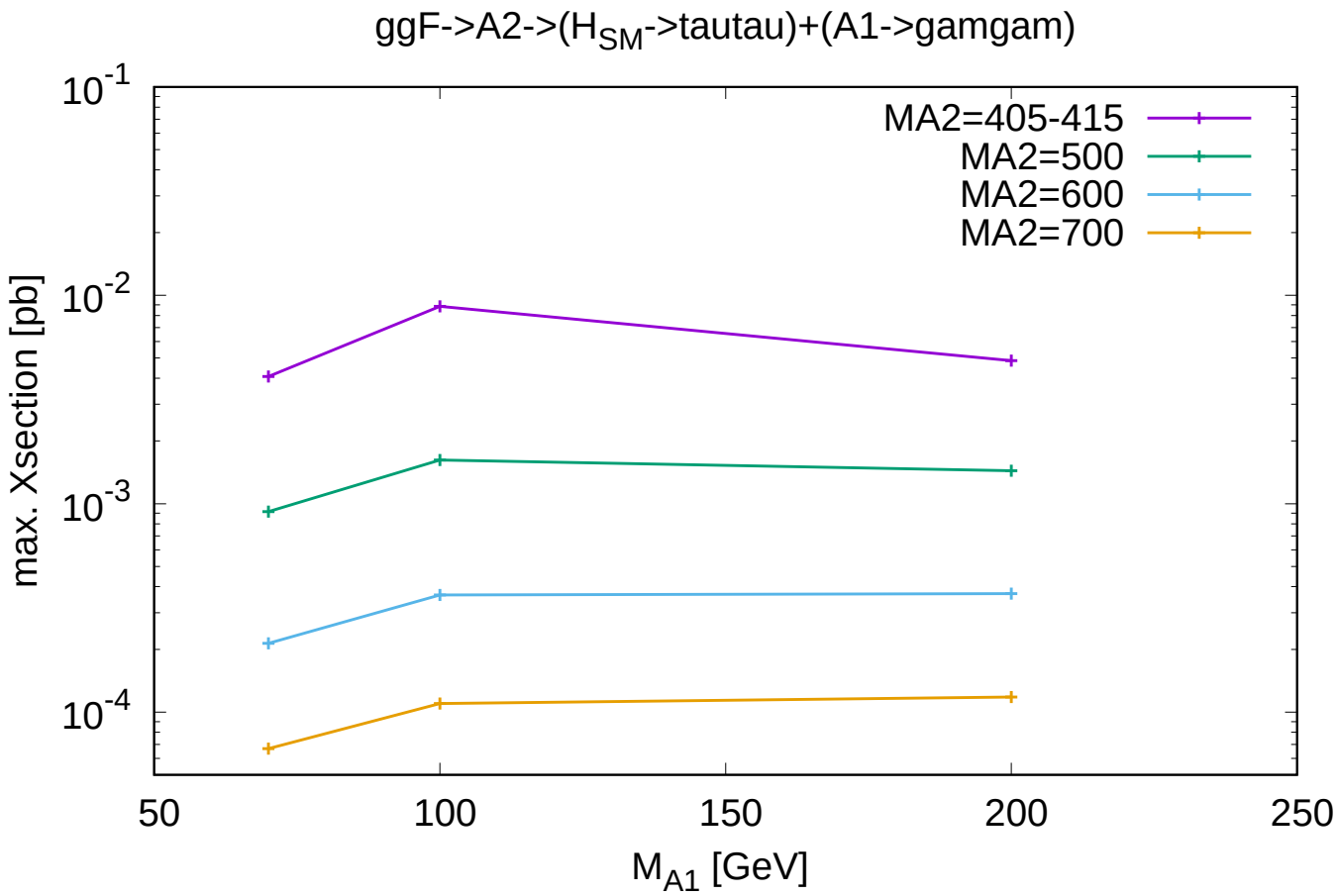
Example: $ggF \to H \to (H_S \to b\bar{b}) + (h \to b\bar{b})$:



- Xsection for $M_{H_S} = 80$ GeV (red):
  For $M_H = 400$ GeV: Limited by the search for $H \to h + h$ by ATLAS
  For $M_H = 500 - 600$ GeV: Limited by the search for
  $H \to (H_S \to b\bar{b}) + h \to \tau\tau)$ by CMS
- Xsection for $M_{H_S} = 200$ GeV for $M_H = 400 - 800$ GeV (blue):
  Limited by the search for $A \to Z + (H_S \to b\bar{b})$ by ATLAS

These searches limit the parameter space of the NMSSM (6 +rad. corrs.)

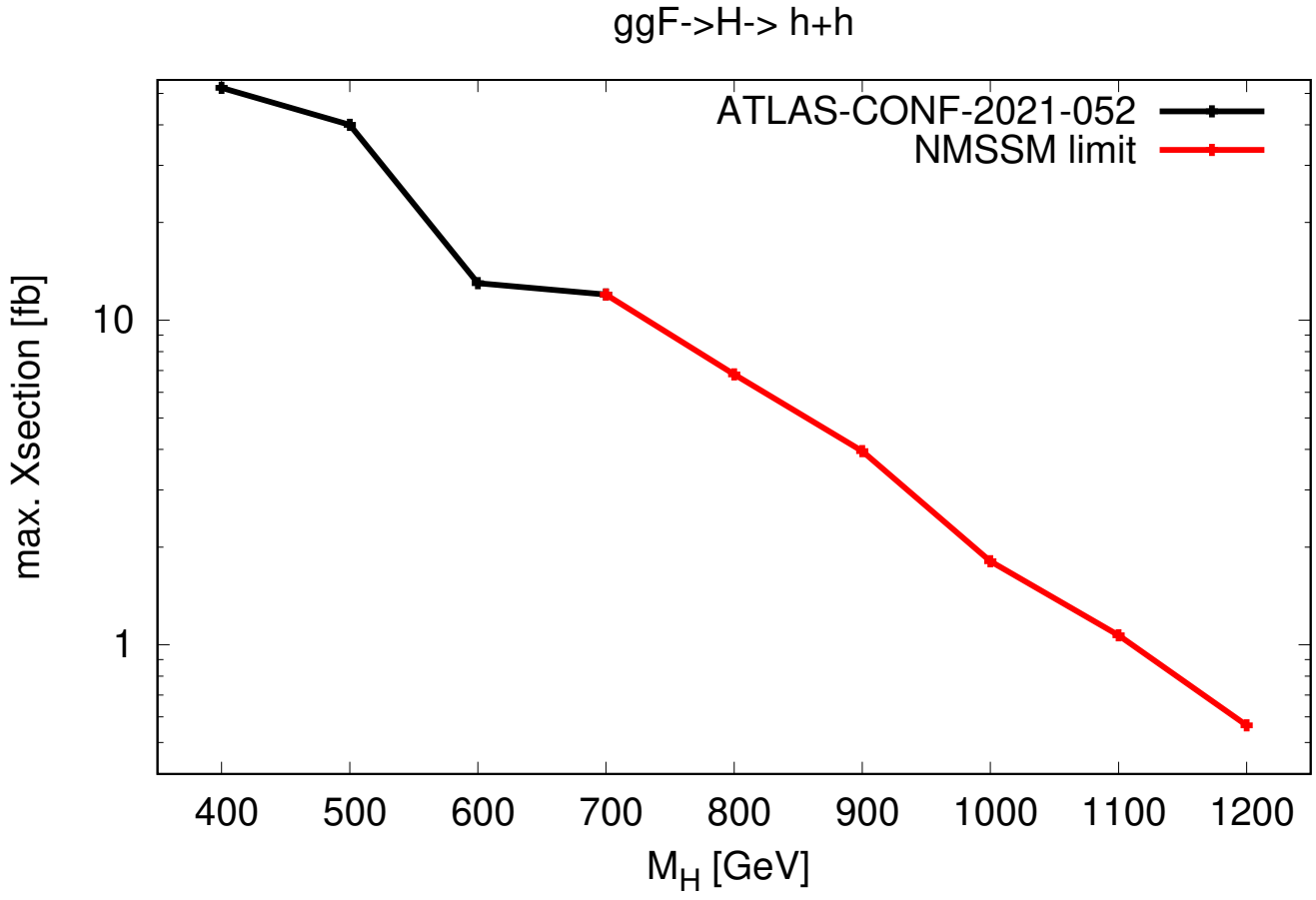
Example: $ggF \to A \to (h \to \tau\tau) + (A_S \to \gamma\gamma)$:



$\to$ Relatively large possible cross sections!

For $M_{A1} \equiv M_{A_S} = 200$ GeV:
The channel $A_S \to Z + \gamma$ is open, contributing $\sim 50\%$.

Resonant SM Higgs Pair Production:



$\rightarrow$ Only for $M_H \gtrsim 700$ GeV the max. cross section in the NMSSM are below the limits from ATLAS-CONF-2021-052 (combination of $b\bar{b} + b\bar{b}, \tau\tau, \gamma\gamma$)

(Non-resonant SM Higgs Pair Production: $\sigma^{hh}_{ggF} \sim 31$ fb)

Conclusions

- Higgs-to-Higgs decays are promising channels for the search of New Physics
- Many (!) possible final states
  (Left aside here: $H^{\pm}$ production, final states with $W^{\pm}$, $h \to A_S + A_S$ for $M_{A_S} < 60$ GeV,...)
- ATLAS/CMS searches have just started, more to come
- Already existing searches are sensitive to viable regions of the parameter space of the NMSSM
- Benchmark planes/lines allow to set targets/to compare sensitivities for the various search channels